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DEVELOPMENT OF A FLYING ROBOT SYSTEM FOR VISUAL INSPECTION OF BRIDGES

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Abstract

Periodical inspection and regular health monitoring are crucial to securing safety and extending the life of bridges. Various destructive and nondestructive bridge inspection approaches with new equipment have been developed. However, most of the current bridge inspection methods, especially bridge appearance inspection methods, require massive assistance facilities and cannot guarantee the inspectors' safety. Hence, developing safe, efficient, accurate and automatic bridge inspection methods are required.

This paper introduces a flying robot system which is combined with an UAV (Unmanned Aerial Vehicles) and a mobile robot for the visual inspection of bridges. The UAV has two coaxial rotors to fly and the mobile robot has omni-directional wheels to navigate the lower surface of the bridges. The developed machine is attached to the lower surface of a bridge using UAV technology and navigates the space autonomously using the mobile platform under the local position recognizable condition with ultrasonic localization system and sends camera images of the surface via wireless communication. This visual inspection flying robot will prevent significant damage of infrastructures such as bridges and large buildings without situating personnel in harmful environments.

INTRODUCTION

Bridges are built to span rivers, valleys, and other obstacles to serve human activity, but when improperly managed bridges can pose threats to the safety of many human beings. Therefore, periodical bridge inspection is crucial; it can extend the life of bridges and consequently guarantee the safety of human beings. The Bridge appearance inspection is one of the most basic and essential bridge inspection methods. However, bridges are usually situated in hard to approach locations so the costs of inspections are potentially very expensive and are often very dangerous for the inspectors. Therefore, numerous efforts have been being made to ensure the safety of the inspectors. As a part of these trials, we have been researching on flying robots capable of observing the bridge appearance.

This research will attempt to show the various realizable applications of a flying robot combined with a mobile robot platform. The flying robot for visual inspection of bridges (hereinafter called FR4VIB) is the extension of flying robot application and the following figures show the concept design of the FR4VIB. The first design is made of ducted fans and omni-directional wheels. The second has coaxial rotors and omni-directional wheels. The development of the FR4VIB is a technically intensive process and is accompanied with the knowledge of flight systems. Alongside this research, we have also developed additional flying robots, which can operate indoors and/or outdoors and have coaxial-rotors or quad-rotors [1-2].

In the next section the hardware system configuration of FR4VIB will show how the system is constructed mechanically and electrically. The localization method which will detect suspicious spots is introduced in the 3rd section. In the 4th section, we will explain the operation of the robot – specifically, the kinematics and dynamics of the omni-wheeled robot, the position calculation process, and the control loop design. The last section concludes the research and points out any apparent weaknesses to overcome.

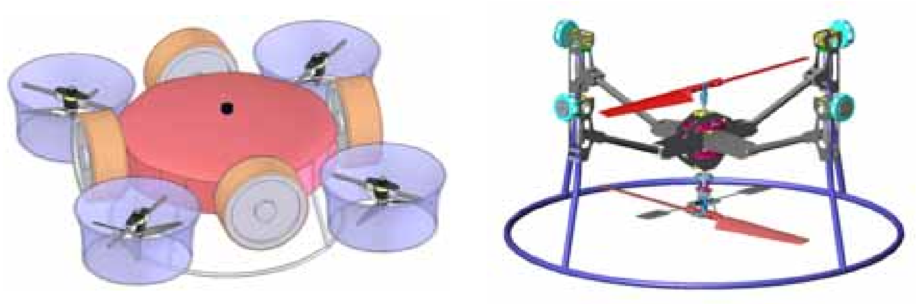


Figure 1. Concept Design of FR4VIB (Left : 1st Prototype, Right : 2nd Prototype).

SYSTEM CONFIGURATION

As mentioned above, the FR4VIB is made for visual inspection of bridges, and therefore has specific configurations. The following sections describe the mechanical and electrical systems and additional sensors of FR4VIB.

Mechanical System

The first prototype of FR4VIB consists of 4 omni-wheeled driving systems and 4 ducted fans and can move on the surface of a ceiling. WEMOTEC's MINI FAN is used as the ducted fan, which differentiates the air pressure between the robot and ceiling in order to attach itself. While maintaining this attaching force, the robot can move along the lower surface of a bridge for inspection. To move towards any direction and to remove the constraints caused by two wheeled system, three or more wheels are needed. Having many wheels increase the robot's mobility but reduce the efficiency of movement. In order to minimize the waste of energy caused by friction, the FR4VIB uses a simple omni-directional wheel mechanism-- Kornylak's Transwheel—for omni-directional wheels and motorBank's GM-16 electric motors for driving the wheels. It can move approximately 15cm per second [3-4].

Table 1: Specification of 1st Prototype of FR4VIB

	Wheel	Motor	Duct fan
manufacturer	Kornylak	motorBank	WEMOTEC
size	ϕ51 x 12 ㎜	ϕ16 x 47 ㎜	ϕ93 x 65 ㎜
weight	23g	58g	60g
feature	omni-wheel (8 mini-wheels)	voltage : DC 7.2V torque : 2.5 ㎏•㎝ planetary gear : 1/130 speed : 60rpm	DC 24V 20A speed : 45000rpm static thrust : 2~14N

Figure 2. Appearance of the 1st Prototype of FR4VIB.

Electrical System

The controller board of the FR4VIB consists of TI's TMS320F2812, Xilinx's 9536 CPLD, L298 motor driver, and other additional components. This board controls the four motors, gets the feedback from four encoders, and communicates some information through RF or another interface. Furthermore, the localization system is needed to recognize the position of the robot, so the ultrasonic positioning system (hereinafter called UPS) is used and is developed to improve the positional accuracy.

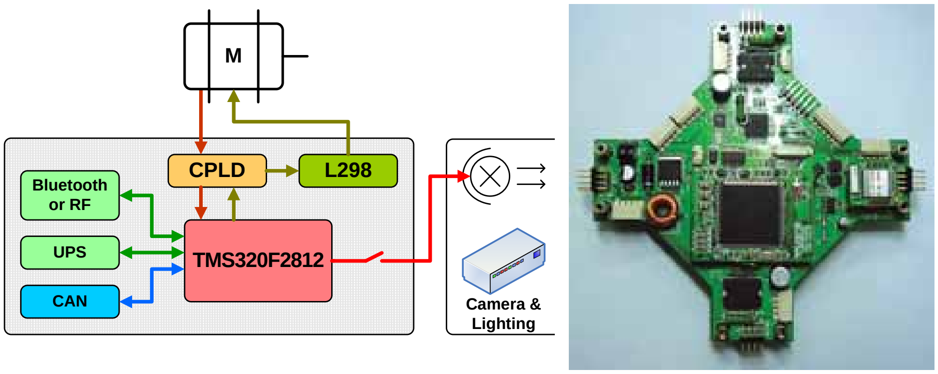


Figure 3. Electrical System Diagram and the Controller Board.

LOCALIZATION

We are developing the UPS, which uses similar principles to the GPS and Cricket – the localization system of M.I.T – in order to increase the accuracy, weight efficiency, and response speed than other established systems [5]. The UPS is composed of a transmitter and many receivers. First, the transmitter broadcasts an RF signal with ultrasonic signals. Then, the receiver within the communicable range detects the RF and ultrasonic signals. After the estimation of distance, the receiver replies to the transmitter with the distance and positional information of itself. If several receivers respond to the transmitter, the transmitter calculates the position of itself using trilateration.

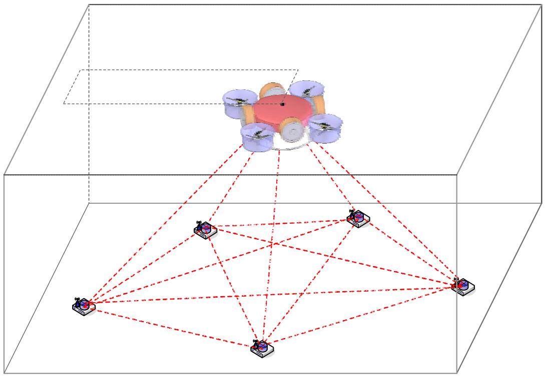


Figure 4. Ultrasonic Positioning System (UPS).

The developed UPS has some difficulties to resolve. The first one is related to the RF signal, which has the role of synchronizing the UPS. This RF signal provides the base time to measure the timing difference of ultrasonic signals. In that case, we can estimate the distance between the transmitter and receiver. However, the RF signal has some delay elements and possibilities of communication failure. So we have to consider producing a seamless communication mechanism. Through some repeated frame of packets we can infer the signal send time, which is essential for measuring the distance. The second issue is to reduce the triangular error. When the distance rate of triangular points has considerable differences, then the trilateration error increases. So we should select the proper node adequate to the trilateration. The larger area which is formed by three points of receivers, the better the points are suitable for the algorithm. Furthermore, the more uniform receivers are scattered to the center of the triangle, the better the points are also suitable. Consequently, the brief formulation is driven as follows [6]:

Y

X

$$\text{maxize}(w_{area} \cdot area_{\,hypothesis} + w_{distance} \cdot dispersion_{\,hypothesis})$$

d3

d1

OPERATION

Rx

Modeling of General Omni-directional Robot

We have simplified the system configuration of the robot for analysis. It is necessary to separate the coordinates of the space as body frame and earth frame. This method is widely used for calculating the mobile motion. The body frame is same as the local frame and the earth frame is same as the global frame. After calculation of the body frame, translation into the earth frame coordinates is performed. In addition to the simplification, some assumptions are needed. There is no slip between the wheels and the ground. There is no slip caused by friction between the moving direction and the omni-wheels laid in the direction of disturbing the movement [7-8].

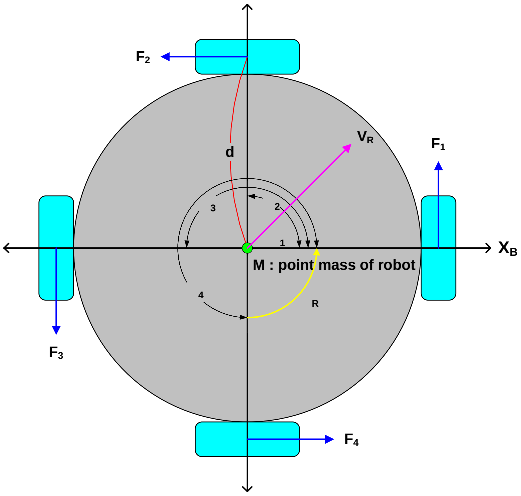
Rx

Rx

The following figure shows the simplified parameters and the following paragraph examines the kinematics and dynamics of the general omni-directional robot. The inertia of the cylinder shape is $1/2 \cdot MR^2$ so it is assumed that the inertia of our robot is $\alpha MR^2 (0 < \alpha < 1)$ [8].

Table 2: Relation Factor of Kinematics and Dynamics

a	acceleration	$\dot{\omega}$	angular rate
C_{α}	force coupling matrix	D	velocity coupling matrix



F_n : force vector
f_n : magnitude of force
θ_n : angle from reference to nth wheel

d : distance from robot center to wheel
r : radius of robot wheel
M : mass of robot
I : Inertia of robot

$v_r \equiv (v_x, v_y, R v_{\omega})^{\mathrm{T}}$
$v_m \equiv (v_1, v_2, \cdots, v_n)^{\mathrm{T}}$

Figure 5. Parameters of robot

$$a = \frac{1}{M}(F_1 + F_2 + \cdots + F_n), \quad \dot{\omega} = \frac{d}{I}(f_1 + f_2 + \cdots + f_n)$$

$$C_{\alpha} = \begin{pmatrix} a_x \\ a_y \\ R\dot{\omega} \end{pmatrix} = \frac{1}{M}\begin{pmatrix} -\sin\theta_1 & -\sin\theta_2 & \cdots & -\sin\theta_n \\ \cos\theta_1 & \cos\theta_2 & \cdots & \cos\theta_n \\ \frac{1}{\alpha} & \frac{1}{\alpha} & \cdots & \frac{1}{\alpha} \end{pmatrix}\begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix}$$

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$$D = \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{pmatrix} = \begin{pmatrix} -\sin\theta_1 & \cos\theta_1 & 1 \\ -\sin\theta_2 & \cos\theta_2 & 1 \\ \vdots & \vdots & \vdots \\ -\sin\theta_n & \cos\theta_n & 1 \end{pmatrix}\begin{pmatrix} v_x \\ v_y \\ R\omega \end{pmatrix}$$

Θ

ω

$$a = C_{\alpha}\, f, \quad v_m = D v_r$$

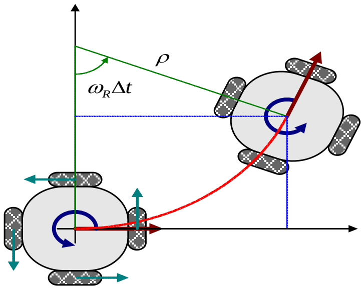
$$\Delta v_r = \Delta t \times a, \quad \Delta v_m = \Delta t \times D C_{\alpha}\, f$$

Omni-directional Movement

Whereas the previous section demonstrated the general omni-motion, the following concerns the FR4VIB. In order to analyze the omni-motion, another rotation to zero translation angle space is needed unlike the two wheeled system. The following procedures show how to calculate the position of an omni-wheeled robot in the earth frame. In the control loop of the FR4VIB, the cyclic calculation is iteratively operated. The first stage is to plan a trajectory through the difference between the current position and the target position so the desired velocity of the robot would be obtained. Next, the PID controller controls the motor velocity by inverse kinematics and encoder feedback.

Observed velocity can be calculated through the encoder feedback and the moving distance is also calculated.

i) Calculate the body frame values from earth frame values.
ii) Calculate the translational velocity (v_T), angle (θ_T) in body frame B.
iii) Rotate the body frame B to B' with θ_T .
iv) Calculate the position in body frame B', shown in figure 6.
v) Rotate the body frame B' to B with $-\theta_T$.
vi) Translate the body frame values to earth frame values.



$$\rho = \frac{v_T}{\omega_R}\ , \quad \omega_R = \frac{v_{w_1} + v_{w_2} + v_{w_3} + v_{w_4}}{4d}$$

$$v_{T_x} = \frac{-v_{w_2} + v_{w_4}}{2}\ , \quad v_{T_y} = \frac{v_{w_1} - v_{w_3}}{2}$$

$$x' = \rho \sin(\omega_R \Delta t)$$

$$y' = \rho(1 - \cos(\omega_R \Delta t))$$

$$\theta' = \omega_R \Delta t$$

Figure 6. Calculation of Movement in Body Frame.

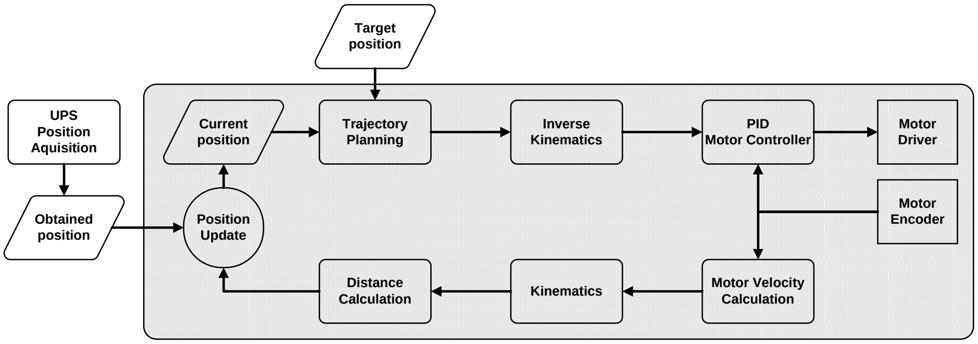


Figure 7. Control Loop Diagram of FR4VIB.

CONCLUSIONS

In this paper, we briefly displayed how to develop the FR4VIB. We have made the first proto-type of the FR4VIB and are in the process of making the second prototype. While developing the first prototype, the main research goal was the omni-motion and localization system, but flying the second prototype is our next mission. The FR4VIB is expected to be useful in many places although the development of the FR4VIB and its related equipment is not easy and have many problems to overcome.

The first hardship concerns trajectory planning. In the first proto-type of the FR4VIB, the entire calculation is operated in the embedded system, so an external control unit is needed and should calculate the planning operation. The next problem is the azimuth angle alignment between the robot and the UPS. In order to know an azimuth angle, a magnetometer is commonly used. However, the large motor affects the accuracy of the sensor. If the magnetometer becomes ineffective, a new approach should be developed, using alignment through the difference between fixed movement and the UPS position.

Desired
XY Veloc

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